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Research Paper

Modelling the settlement behaviour of a strip footing on sloping sandy fill under cyclic loading conditions

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ABSTRACT

This paper investigates the settlement behaviour of a strip footing seating on the crest of an embankment and subjected to cyclic loading. The embankment fill is a dense sand and the issue is the gradual accumulation of settlement over a large number of load repetitions. Cyclic triaxial tests were first conducted to develop a consistent but simple material model for numerical implementation. Particular emphasis was placed on linking the stress-strain behaviour of an unload-reload cycle to the accumulation of permanent strain, with only five input parameters required to model the cyclic behaviour. The material model was implemented in a numerical analysis to compute the settlement behaviour obtained from model tests conducted by another researcher. It is pertinent to highlight that the same soil, compacted to same density at same moisture content, was used for both the cyclic triaxial tests and model tests. Reasonable to good agreement between the experimental and numerical results was achieved.

1. Introduction

In many practical cases, footings need to be constructed on or near the crest of a fill slope, for example, a bridge abutment supported by an embankment slope. The loading on this type of footing consists of dead load, sustained live load and cyclic live load. In practice, the design of a footing is often based on approximations by considering an 'equivalent' monotonic load and the use of a large factor of safety. It is pertinent to note that this type of footing rest on well-compacted soil and is under a dominantly vertical concentric loading. Therefore, the design issue is mainly about the accumulation of settlement under a large number of loading cycles which is the main subject of investigation in this article.

Publications on experimental investigations of the behaviour of model footing on an embankment slope subjected to cyclic loading conditions are limited. A recent experimental study on the behaviour of a strip footing on a loosely compacted sandy fill slope under cyclic loading was performed by Sawwaf and Nazir [1]. The investigation was focused on the effects of the cyclic loading amplitude and frequency, and footing setback distance on the settlement behaviour of the footing. Systematic experimental studies on a strip footing on dense sandy fill slope were also performed by Islam and Gnanendran [2] and Islam [3] where the effects of cyclic loading amplitude and frequency, and the slope angle on the settlement behaviour of the footing were investigated. Empirical equations were proposed to represent the observed permanent settlement of the footing under cyclic loading. However, there are severe challenges in utilising the findings of these limited model studies to predict performances under field conditions. On the other hand, due to the difficulties, resources and time involved, prototype and large scale laboratory experiments are not feasible. An effective alternative or supplement is to perform numerical studies.

Numerical studies of shallow foundations available in the literature are limited mainly to static loading conditions [4–7]. Published literature on numerical studies on response of a footing on well-compacted soil to cyclic loading is also limited [8–10]. A numerical investigation of the settlement behaviour of footings on sand under cyclic loading conditions was conducted by Boushehrian et al. [8] using the finite element computer program *PLAXIS3D*. The soil elements were modelled using the in-built hardening soil model of *PLAXIS*. Input parameters could be selected to give a reasonable match with the experimental data. However, the hardening soil model of *PLAXIS* could not capture the accumulation of permanent strain in an unload-reload cycle at an element (soil model) level. It appeared that the computed accumulation of permanent settlement with load cycles was due to the stress re-distribution and change of stiffness properties of the soil with

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load cycles. Also, analyses were performed for only about 20 loading cycles which is inadequate compared to most practical bridge abutment conditions. Another numerical study of a footing on silica sand of a range of densities under cyclic loading condition was conducted by Tafreshi et al. [9] using *FLAC3D*. It was reported that the Mohr-Coulomb (MC) material model was used for the soil elements, and a rigid circular footing was used to apply cyclic loading on the foundation. The stress-strain responses obtained from the numerical analyses were compared with the model test data for the first few loading cycles. However, the permanent settlement behaviour of the footing was not reported in this study. It is noted that the MC material model in *FLAC* is a strength model with the stiffness modelled by a Young's modulus. Thus it is not clear how the accumulation of residual strain or permanent footing settlement is captured. Furthermore, neither of the studies considered involvement of slope in the foundation.

In order to adequately predict the accumulation of permanent deformation with load cycles (N), one needs a soil model that can capture the unload-reload stress-strain behaviour, and link it to the accumulation of permanent strain. A number of such models are available in the literature [11–14]. However, the input parameters for these models are difficult to determine. Furthermore, these models were developed mainly for loose to medium dense sand and calibrated for a small number of load cycles, typically less than 20, for liquefaction behaviour. For the situation of a well-compacted sandy soil, with a slow rate of strain accumulation but subjected to many load cycles, an alternative modelling approach originated mainly from pavement engineering is to idealise the unload-reload response as characterised as elastic (and referred to as resilient). This means the accumulation of permanent strain in an unload-reload cycle is not modelled. The accumulation of permanent strain or deformation with load cycles, often expressed as a multiplier of the resilient strain, is separately established by empirical correlations. Such an artificial decoupling means the behaviour of a boundary-value problem under cyclic loading cannot be traced in a numerical analysis. A number of factors including stress level, amplitude and frequency, number of load cycles, density and moisture content of the soil etc. can be empirically considered in this approach. However, this is fundamentally an 'equivalent' monotonic approach with a number of empirical correlations being built into the 'equivalence'.

The development of cumulative permanent strain ($\varepsilon^{p}_{a(N)}$) in a granular soil at Nth loading cycle is a gradual process where a small increment of permanent strain (i.e., $\Delta\varepsilon_{a(N)}$) accumulates in Nth loading cycle. The stress level is also one of the most important factors that affects the development of $\varepsilon^{p}_{a(N)}$ of granular soil [15–17]. An early study performed by Morgan [17] suggested that $\varepsilon^{p}_{a(N)}$ is related to confining pressure (σ_3) and cyclic deviatoric stress (Δq). $\varepsilon^{p}_{a(N)}$ for granular soil is also significantly affected by the density of the soil where $\varepsilon^{p}_{a(N)}$ decreases with the increase of relative density [18,19]. Under cyclic loading conditions the moisture content plays an important role where permanent strain resistance and stiffness of a granular soil decreases with the increase of moisture content [20,21]. The stiffness of a granular soil increases and the ratio of the permanent to resilient deformation decreases during subsequent load cycles. A number of correlations are available in the literature to empirically predict $\varepsilon^{p}_{a(N)}$ of the granular soil under cyclic loading conditions [16,22,23]. However, at the time of conducting this study, the authors were not aware of any formulation which could accurately model and predict the accumulation process of $\Delta\varepsilon_{a(N)}$ and their variation with N.

The investigation in this paper is presented in two parts. The first part discusses about the development of a relatively simple model for dense sandy soil that can trace the unload-reload stress-strain behaviour over a large number of load cycles and link it to the accumulation of permanent strain, that is the cyclic loading is an integral part of the soil model. This is achieved by conducting cyclic triaxial tests under different combinations of confining pressure and cyclic deviatoric stress. In the second part, the proposed material model is implemented in a numerical analysis using *FLAC2D* [24] and verified against model testing results. The model parameters for the prediction were objectively obtained from cyclic triaxial tests, whereas the model tests were those reported independently by Islam [3].

2. Experimental investigations

The experimental investigation reported in this article consists of two parts: (i) triaxial testing to provide monotonic and cyclic stress-strain data for establishing a soil model; and (ii) model testing for validation of the numerical predictions.

2.1. Tested soil

The same soil was used for both the triaxial and model tests. It is a locally available well-graded sand with about 5% non-plastic fines. The particle size distribution curve of the soil is shown in Fig. 1. The maximum dry density (MDD) and optimum moisture content (OMC) were determined from Standard Proctor compaction test and found to be 1819.5 kg/m^3 and 4.75% respectively. A series of monotonic triaxial tests were conducted first at different confining pressures ranging from 50 to 200 kPa for the objective determination of the soil strength and deformation parameters. The measured friction angle (ϕ), dilation angle (ψ) and cohesion (c) was found to be 44^0, 13^0 and 8.2 kPa respectively. It should be noted that all the triaxial specimens were compacted at MDD with OMC which were consistent with the large scale laboratory model footing tests as described later.

2.2. Triaxial test

2.2.1. Triaxial testing arrangement

The triaxial station can perform both monotonic and cyclic triaxial tests and can switch seamlessly between different testing modes as described in detail by Craciun [25]. Soil specimens with 100 mm diameter and 200 mm height were tested. A servo-controlled actuator, connected with the top platen of the specimen, was used to apply axial force on the specimen. Applied axial force was measured using an internal load cell placed above the top platen inside the triaxial cell. The axial deformation of the specimen

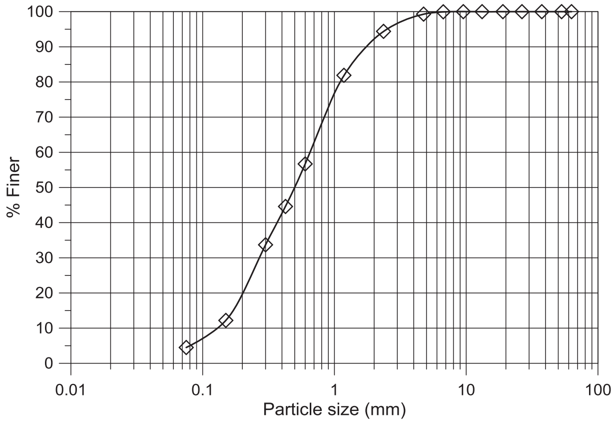

Fig. 1. Particle size distribution curve of tested soil.